INTERIM PROGRESS REPORT

Project Title: Forecasting the Condition of Sea Ice on Weekly to Seasonal Time Scales

PI: Dr. Ignatius G. Rigor
Polar Science Center, AppliedPhysics Laboratory
University of Washington,
Seattle, WA 98105
Phone: (206) 685-2571
Fax: (206) 616-3142
Email: ignatius@apl.washington.edu

Co-PI's: Dr. Pablo Clemente-Colon & Lt. John Wood
National/Naval Ice Center
NSOF, Room 1743,
4251 Suitland Road,
Washington, D.C. 20395
Phone: 301-394-3105
Fax: 301-394-3200
Email: Pablo.Clemente-Colon@natice.noaa.gov

NOAA Grant Number: NA17RJ1232

Time period covered: July 1, 2007 - June 30, 2008.

I. Preliminary Materials

A. Project Abstract

The Arctic has long been considered a harbinger of global climate change since numerical simulations of global climate change predict that if the concentration of CO_2 in the atmosphere doubles, the greenhouse warming signal will be much greater at high latitudes. This "polar amplification" of the global warming is attributed to changes in sea ice and snow (ice-snow albedo feedback). Indeed, many studies of the observational records show polar amplification of the warming trends, and four of the last seven summers have set record minima for Arctic sea ice extent. Could we have predicted these past minima? Through this project, we plan to answer this question, and hope to improve our operational capability to predict the conditions of Arctic sea ice so we can forecast future minima with demonstrable skill.

The proposed work stems naturally from the long standing collaboration between the National/Naval Ice Center (NIC) and the Polar Science Center (PSC) which have been working together to maintain the network of drifting buoys on the Arctic Ocean as part of the International Arctic Buoy Programme (IABP; http://iabp.apl.washington.edu/). The IABP provides observations that support both operational weather and ice forecasting, and climate research (Figs. 1 and 2). In this proposal we plan to improve the operational capability of the NIC to predict Arctic sea ice conditions on weekly to seasonal time scales.

The forecasts provided by the NIC help resources managers, navigators and hunters make better decisions regarding Arctic sea ice. Accurate sea ice information is important to Naval operations. Accurate routing information through ice, based on models that have been designed to predict ice thickness and ice motion is imperative to decreasing operating costs and increasing safety of life at sea.

This project relies heavily on many interagency and international partnerships. The NIC cooperates with the CIS, therefore, forecasts produced by this project will be developed in collaboration with CIS. The Principal Investigators also collaborate with the International Arctic Buoy Programme (IABP) to deploy buoys which monitor air, ice and ocean conditions, i.e. observations required by this project.

This project will be managed in accordance with the Ten Climate Monitoring Principles. Specifically, we plan to transition research that has improved our understanding of sea ice variability towards better ice forecast products; climate research new forecast products will be provided in concert with existing products; our methods and data will be documented in peer reviewed publications and through our web pages (e.g. http://www.natice.noaa.gov and http://seaice.apl.washington.edu/Outlook/).

B. Objective of Research Project

Update and improve the National Ice Center's ability to forecast sea ice using new observations and results from climate research by:

1.) Validating and improving ice growth models using new *in situ* observations of surface air temperature, ice and ocean temperatures, and ice thickness (Figs. 1 and 2) obtained by the IABP, and funded by NOAA.

2.) Exploiting the significant lag correlations between surface air temperature (SAT) and sea ice extent with large scale variations in atmospheric circulation (e.g. the Arctic Oscillation (AO), and the relationship between the age (thickness) of sea ice and summer sea ice extent to produce long range forecasts/outlooks of Arctic sea ice conditions.

C. Approach

1. Gerson Ice Growth Model

The investigators have been deploying buoys enhanced to monitor a myriad of geophysical variables in collaboration with other participants of the IABP. We will use these observations to assess/validate and if possible, improve the Gerson and Perchal (1973) Ice Growth Model. For example, in Fig. 2 (right) we show the observations from an Ice Mass Balance (IMB) buoy deployed in the Beaufort Sea of the Arctic Ocean. In addition to the basic meteorological variables of sea level pressure and surface air temperature, the IMB buoys also monitor ice thickness and ice temperatures, snow depth, and ocean temperatures. So far, over a dozen IMB buoys have been deployed throughout the Arctic Ocean, 5 IMB buoys are currently reporting (Fig. 1), and the participants of the IABP plan to deploy 7 more this summer. The IMB buoy data are collected through the Argos satellites system and analyzed by the investigators.

The NIC's current methods of identifying ice types and estimating ice thickness rely upon a model developed by Gerson and Perchal (1973) uses Zubov's (1943) ice growth equations, which are based on empirical relationships derived from observations of air temperature and ice growth in the Russian marginal seas of the Arctic Ocean. Using the IMB observations (e.g. Fig. 2) we can validate the parameters in the empirical ice thickness equations and improve the accuracy of the NIC's ice typing and thickness products.

2. Lag Correlations between winter sea ice and the Arctic Oscillation

It has been shown that many of the changes in Arctic climate and sea ice are related to large scale modes of climate variability, e.g. the Arctic Oscillation (AO, Thompson and Wallace, 1998). The AO explains more than 54% of the variance in SLP during winter and over 36% during summer over the Arctic Ocean, and thus many of the changes in Arctic climate are highly correlated to variations in the AO, e.g. through the advection of heat and redistribution of sea ice by the wind.

Short term sea ice forecasts may benefit from the 2-week AO forecasts provided by NCEP, and from the predictability of the AO on slightly longer time scales (60 days) due to its coupling with the stratosphere (e.g. Baldwin and Dunkerton, 2001).

On seasonal and longer times scales, significant lag correlations have been found between summer sea ice conditions and the atmospheric conditions up to a few seasons in advance, i.e. winter weather patterns leave an imprint on the sea ice that can be observed the following spring, summer and fall. These correlations can be used in single and multivariate prediction schemes

In summary, the prior winter AO-index explains as much as 64% of the variance in summer sea ice extent in the Eurasian sector of the Arctic Ocean (Rigor et al. 2002), but the winter and summer AO-indices combined explain less than 20% of the variance along the Alaskan coast. However, the age of sea-ice explains 50 – 80% of the year-to-year variability of summer sea ice extent (Rigor and Wallace, 2004). We plan to take advantage of the significant lagged correlations between the AO and sea ice to predict Arctic sea ice conditions months in advance.

D. Description of any matching funds used for this project

For cost-sharing with the NOAA TRACS, the PSC/APL/UW will cover 5% of our APL proposed budget, for a total contribution of $12,971. The salaries of LT Magda Hanna, LT John Woods, Dr. Pablo Clemente-Colon, and an Ice Analyst at the NIC come at no cost to the budget for this proposal. This amounts to $32,400/FY, a cost share from NIC of 53.3% of the total subcontract budget for this project. The total combined cost share of $110,171 is based on our budget request of $441,682, and is 24.9% of the total budget request.

II. Interactions

A. Description of interactions with decision-makers who were either impacted or consulted as part of the activity; include a list of the decision makers and the nature of the interaction; be explicit about collaborating local institutions.

The NIC provides satellite images of sea ice and analyzed fields of sea ice conditions to support the US Coast Guard and Canadian ice breakers. Observations of sea ice concentration and thickness collected by Sea Ice Observers on board these ice breakers have been obtained to validate our sea ice analysis. Through this collaboration, we hope to improve the use of our sea ice forecasts for navigation in the Arctic Ocean.

We have also begun collaboration with Shell Oil to deploy and analyze data from buoys in the land-fast sea ice areas along the northern Alaskan coast. Through this collaboration, we hope to improve the use of our sea ice forecast products by coastal decision-makers.

Drs. Rigor and Clemente-Colon are members of the Alaska Ocean Observing System (AOOS) Sea Ice Working Group which was established to develop strategies to further our knowledge of coastal sea ice, and meet stakeholder and resource management needs in Alaska.

B. Description of interactions with climate forecasting community

Operational prediction of sea ice conditions for the United States (and the world) is provided by the National/Naval Ice Center, which is an interagency collaboration between the Navy, NOAA, and the Coast Guard.

III. Accomplishments

A. Brief discussion of research tasks accomplished. Include a discussion of data collected, models developed or augmented, field work undertaken.

Initial funding for this project was received in November 2005.

1. Data Collection and Analysis

This project leverages the collaboration of the NIC and PSC in the IABP (Fig. 1). Observations of sea ice growth and surface air temperature from the Ice Mass Balance (IMB) buoys (e.g. Fig. 2) deployed by the IABP, have been used to assess and validate the Gerson and Perchal (1973) Ice Growth Model using data through 2004. Data from these buoys through 2006 have been collected and will also be used in the continued assessment and validation of the Ice Growth Model.

Estimates of the age of sea ice, which are used to predict summer sea ice extent, have been analyzed through June 2006. These estimates of the age of sea ice on the Arctic Ocean have been included in the NOAA State of the Arctic Ocean reports for 2005, and the NOAA Annual Report: The State of the Ocean and the Ocean Observing System For Climate for 2005, and will also be included in these reports for 2006 (e.g. Fig. 3)

Observations of sea ice drift from the IABP, and sea ice concentration from Dr. Josephino Comiso (NASA) have now been collected through December 2006, and will be used to update the estimates of the age of sea ice through 2006.

Preliminary results of these analyses will be discussed in Section III.B. below.

2. We have hired a Visiting Scientist at the NIC to help develop, and implement improvements to the sea ice growth model, and sea ice forecasts (more details on this hire are provided in Section III.D.).

B. Summary of any preliminary findings (i.e., how this research advances our scientific understanding)

The primary objectives of this project are to:

1. Reevaluate of the Gerson and Perchal (1973) Ice Thickness (Growth) Model

As noted in Section I.C.1. the NIC's current methods of identifying ice types and estimating ice thickness rely upon a model developed by Gerson and Perchal (1973) and uses Zubov's (1943) ice growth equations, which are based on empirical relationships derived from observations of air temperature and ice growth in the Russian marginal seas of the Arctic Ocean. Observations of sea ice growth and temperature from the IMB buoys deployed from 1997 to 2004 have been analyzed to assess the accuracy of the Gerson and Perchal (1973) Ice Growth Model. In Fig. 2 (left) we show the observed sea ice thickness measured by the IMB buoys and the sea ice thickness predicted by the Gerson and Perchal (1973; aka Zubov, 1943) Ice Growth Model based on the surface air temperature observations at each IMB buoy. This figure shows that, in general, the Ice Growth Model can predict the growth of sea ice during winter (note that most of the points are on the diagonal line), however, there are significant errors in the predicted ice growth during fall and when a deep layer of snow insulates the sea ice (e.g. deviations from the line shown in Fig. 2 right). We attribute the delay in ice growth during fall to the heat absorbed by the sea ice and ocean that is not accounted for Ice Growth Model.

These results may be used to improve the Ice Growth Model at the NIC. Just as the Ice Growth Model is based on a sum of Freezing Degree Days, we can use the observed air, ice and ocean temperatures from the IMB buoys during summer to measure the heat content (e.g. Heating Degree Days) at each buoy and predict the "delay" in ice growth during fall.

The IMB buoys also measure snow depth (Fig. 2, right). While these are only "point" measurements at a few locations across the Arctic Ocean (e.g. Fig. 1), Warren et al. (1999) estimate that the error of a point measurement is only about 7 cm, i.e. the IMB observations of snow may provide enough accuracy to at least determine if the snow is thick enough to hinder ice growth.

Data from IMB buoys deployed in 2005 and 2006 will be analyzed similarly during the next two months. And we begin implementation of these improvements at the NIC when Todd Arbetter reports on April 1, 2007.

2. Implement Long-Range Sea Ice Forecasts

Our weekly and longer sea ice forecasts rely on the significant lag-correlations between sea ice conditions and variations in large-scale modes of climate variability such at the Arctic Oscillation (e.g. Fig. 3 of our original proposal), and the age of sea ice. E.g. the age of sea ice is highly correlated to summer sea ice concentration and extent (e.g. Figs. 4 & 5 of our original proposal), and the area of multi-year ice on the Arctic Ocean (Fig. 3). These correlations can help us develop sea ice outlooks for the Arctic Ocean.

This year most of our work as been to validate the age model, and understand the correlations between the age of sea ice and sea ice conditions. As we have shown, the age of sea ice is a good predictor of summer sea ice conditions (e.g. Fig. 5 of our original proposal), however, better prediction models may be developed if we can improve our understanding of the physical basis for these correlations. Towards this end, we have been comparing our age of sea ice estimates with measurements of sea ice thickness (e.g. data from the IMB buoys, and submarine ice draft), and satellite derived estimates of the areas of multi-year sea ice (e.g. Fig. 3). As hypothesized in our proposal and publications, the age of sea ice is highly correlated to the amount of ridging and rafting over a large area of sea ice. Multi-year sea ice has seen more storms, and thus has more ridges and is thicker both from having more time to grow through the cold winters, and by storm dynamics.

Fig. 3 shows the comparison of the age of sea ice in March 2006 with estimates of the area of multi-year (perennial) sea ice for March 21, 2006 derived from QuikSCAT satellite data (Richter-Menge et al, in preparation). Note the strong correspondence between the areas of older sea ice (left) based on our age model and areas of multi-year ice (right) based on the satellite data. These results give us confidence that our predictions for sea ice conditions during the following summer will have skill, i.e. areas of younger, sea ice should be thinner and thus easier to navigate.

During the next year, we will refine our sea ice forecast models as we work to implement these forecasts at the NIC.

References:

Richter-Menge, J.A., and many others including **I.G. Rigor**, State of the Arctic. *FY 2006 NOAA Annual Report: The State of the Ocean and the Ocean Observing System For Climate,* NOAA Office of Climate Observation, in preparation.

Rigor, I.G., J.M. Wallace, and R.L. Colony, Response of Sea Ice to the Arctic Oscillation, *J. Climate*, v. 15, no. 18, pp. 2648 - 2668, 2002.

Rigor, I.G. and J.M. Wallace, Variations in the Age of Sea Ice and Summer Sea Ice Extent, *Geophys. Res. Lett.*, v31, doi:10.1029/2004GL019492, 2004.

Warren, S.G., **I.G. Rigor**, N. Untersteiner, V. F. Radionov, N. N. Bryazgin, Y. I. Aleksandrov, and R. Colony, Snow Depth on Arctic Sea Ice, *J. Climate*, v. 12, no. 6, pp. 1814–1829, 1999.

Zubov, N. N., 1943: Arctic Ice (in Russian). Glavsevmorputi, 360 pp. (English translation, Transl. 103, U.S. Navy. Electr. Lab., San Diego, CA.)

C.1. Publications during the past year.

Clemente-Colón, P. and W.G. Pichel, 2006: Remote Sensing of Marine Pollution, *Remote Sensing of the Marine Environment*, J. Gower (Editor), *Manual of Remote Sensing*, Third Edition, v. 6, A. N. Rencz, Editor-in-Chief, ASPRS, ISBN 1-57083-080-0.

Intergovernmental Panel on Climate Change (IPCC) Working Group I, Contribution to the Fourth Assessment Report of the IPCC - *Climate Change 2007: The Physical Science Basis*. (Rigor, I.G. is a Contributing Author on Chapter 4: Observations: Changes in Snow, Ice and Frozen Ground.).

Monaldo,F.M., D.R.Thompson, N.S.Winstead, W.G.Pichel, **P.Clemente-Colón**, and M.B. Christiansen, 2005: Ocean Wind Field Mapping from Synthetic Aperture Radar and Its Application to Research and Applied Problems, *JHU/APL Tech. Digest*, v. 26, n. 2, 102-113.

Nghiem, S.V., Y. CHao, G. Newumann, P. Lii, D.K. Perovich, T. Street, and **P. Clemente-Colón**, 2006: Depletion of perennial sea ice in the East Arctic Ocean, GRL, v. 33, L17501, doi:L10.1029/2006GL027198.

Richter-Menge, J., J. Overland, A. Proshutinsky, V. Romanovsky, L. Bengtsson, L. Brigham, M. Dyurgerov, J.C. Gascard, S. Gerland, R. Graversen, C. Haas, M. Karcher, P. Kuhry, J. Maslanik, H. Melling, W. Maslowski, J. Morison, D. Perovich, R. Przybylak, V. Rachold, **I.G. Rigor**, A. Shiklomanov, J. Stroeve, D. Walker, and J. Walsh, State of the Arctic. NOAA OAR Special Report, NOAA/OAR/PMEL, Seattle, WA, 2006, 36 pp. (This Report may be obtained from http://www.pmel.noaa.gov/pubs/PDF/rich2952/rich2952.pdf.)

Richter-Menge, J.A., and many other including **I.G. Rigor**, State of the Arctic. *FY 2005 NOAA Annual Report: The State of the Ocean and the Ocean Observing System For Climate,* ed. Diane M. Stanitski, NOAA Office of Climate Observation, Silver Spring, MD, 20910. USA, 2006.

Richter-Menge, J.A., D.K. Perovich, B.C. Elder, K. Claffey, **I.Rigor**, M. Ortmeyer, Ice Mass Balance Buoys: A tool for measuring and attributing changes in the thickness of Arctic sea ice cover, Annals of Glaciology, v. 44, 2006. (This paper may be obtained from http://seaice.apl.washington.edu/Papers/Richter-MengeEtal2006_IMB.pdf.)

Sasaki, Y.N. Y. Katagiri, S. Minobe, and **I.G. Rigor**, Autumn atmospheric preconditioning for interannual variability of wintertime sea-ice in the Okhotsk Sea, J. Oceanography, accepted, 2007.

Serreze, M.C. and **I.G. Rigor**, The cryosphere and climate change: perspectives on the Arctic's shrinking sea ice cover., *Glacier Science and Environmental Change,* ed. P. Knight, Blackwell Publishing, Ltd, Oxford, August 2006.

C.2. Presentations during the past year.

Alkire, M.B, K.K. Falkner, J. Morison, **I. Rigor**, and M. Steele, The Return of Pacific Waters to the Upper Layers of the Central Arctic Ocean, *Eos Trans. AGU, 87(52)* Fall Meet. Suppl., Dec. 2006.

Darby, D.A., M. Jakobsson, **I. Rigor**, New Insights in Sea Ice Drift Based on Dirty Ice Samples Collected in 2005 by the HOTRAX Expedition, *Eos Trans. AGU, 87(52)* Fall Meet. Suppl., Dec. 2006.

Moritz, R.E. and **I. Rigor**, Research Applications of Data from Arctic Ocean Drifting Platforms: The Arctic Buoy Program and the Environmental Working Group , *Eos Trans. AGU, 87(52)* Fall Meet. Suppl., Dec. 2006.

Rigor, I.G. (INVITED), Sea Ice, NOAA Climate Observation Program, 4th Annual System Review, Silver Spring, MD, May 2006.

Rigor, I.G. (INVITED), Interdecadal Variations in Arctic Climate and Sea Ice, Alaska Fisheries Science Center (AFSC/NOAA) Seminar, Seattle, WA, Feb. 2006.

Rigor, I.G. (INVITED), Interdecadal Variations in Arctic Sea Ice, Woods Hole Oceanographic Institute (WHOI) Physical Oceanography Seminar, Woods Hole, MA, Feb. 2006.

Rigor, I.G., M. Hanna, M. Ortmeyer, An Outlook for Summer sea ice north of Alaska, Proc. Marine Sciences of Alaska Symposium, Anchorage, AK, Jan. 2006.

D. Discussion of any significant deviations from proposed work plan

Lt. John Woods has relieved Lt. Magda Hanna as Science Officer at the NIC, and Dr. Pablo Clemente-Colon and Lt. Woods have assumed Principle Investigator responsibilities for this project at the National Ice Center.

We have also hired Dr. Todd Arbetter as a Visiting Scientist at the NIC to assist in the operational implementation of our sea ice forecasts. Dr. Arbetter received his Ph.D. from the University of Colorado in 1999, and is currently a Senior Scientific Officer at the British Antarctic Survey. Since Dr. Arbetter is an experienced Scientist, we have offered him a higher salary than the post-doc position we originally budgetted for. This extra cost will be covered by other grants from the NIC and the PSC.

IV. Relevance to the field of human-environment interactions

A. How is your project explicitly contributing to the following areas?

1. Natural Hazards Mitigation

The Arctic Ocean has been predicted to be “ice free” during summer by 2040 (e.g. IPCC, 2007). This alarming decline of sea ice has profound social and economic implications, e.g. navigation through the Arctic Ocean will increase, as will threats to our National Security. During the summer of 2005 the Eurasian side of the Arctic was wide open, while on the American side, only 70 miles of the Canadian Archipelago was blocked up by sea ice. Our forecasts may be able to provide critical outlooks for summer sea ice conditions, e.g. when will the navigation lanes through the Arctic Ocean open.? Where will the younger, thinner sea ice that is easier to navigate be? As shown in Fig. 3, most of the younger, thinner sea ice is currently on the Eurasian side of the Arctic Ocean, however, a return to low Arctic Oscillation conditions may sweep the older, thicker ice that now resides on the American side into the Eurasian side of the Arctic Ocean. Knowledge of current sea ice conditions and being able to predict changes in these conditions are critical for our ability to respond to global climate change.

2. Economic value of climate forecasts

The ability to predict summer sea ice extent and the navigability of the Northwest Passage and Northern Sea Route months in advance may allow society to realize some economic savings since these routes from Europe to Asia are as much as 60% shorter than conventional routes. Accurate routing information through ice, based on models that have been designed to predict ice thickness and ice motion is imperative to decreasing operating costs and increasing safety of life at sea. And understanding the changes in sea ice may help native cultures who hunt and live at the sea ice edge.

3. Developing tools for decision makers and end-users

We plan to improve the NIC's ability to predict Arctic sea ice conditions on weekly to seasonal time scales. Knowing the current and future conditions of Arctic sea ice directly impacts daily operations of ships and submarines in the Arctic. For example, one of the top three requests from ships and submarines is operational ice thickness.

4. Matching new scientific information with local/indigenous knowledge

Our estimates of the age of sea ice are being compared to "local" information from Ice Breakers operating in the Arctic Ocean, with data from Shell Oil (as noted in Section II.A.), and satellite data (e.g. Section III.B.2).

V. Website address for further information (if applicable):

Information about this project are available from http://seaice.apl.washington.edu/Outlook/, and http://www.natice.noaa.gov/. We will also provide our sea ice forecasts through these web pages.

VI. Graphics

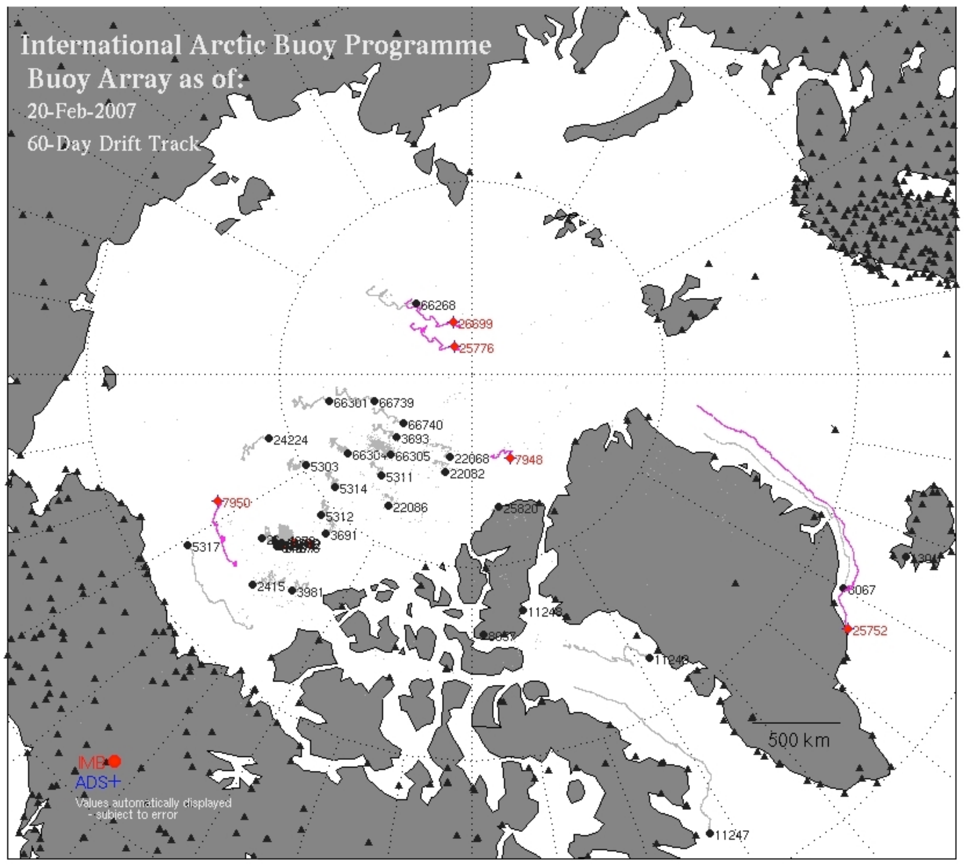

Figure 1: Location of Ice Mass Balance (red dots) buoys used for validation of the Gerson and Perchal (1973) Ice Growth model, and IABP buoys (black dots) used to estimate the age of sea ice on the Arctic Ocean on reporting Feb. 20, 2007.

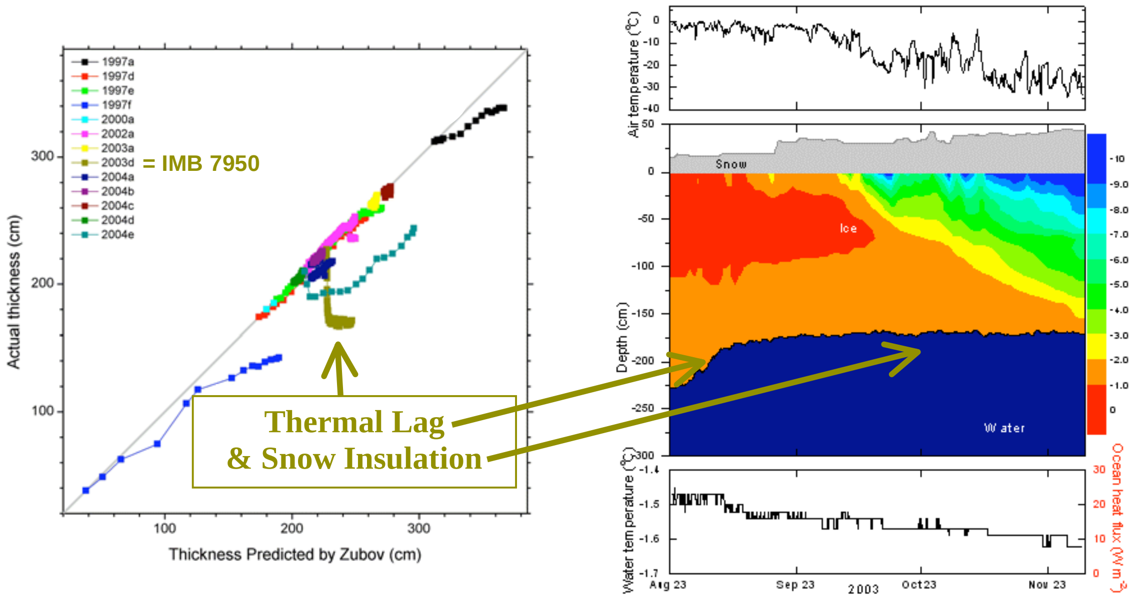

Figure 2: Observations from Ice Mass Balance (IMB) buoy 7950 (right), and comparison of the observed sea ice growth from the IMB buoys with the expected growth of sea ice based on the Zubov (1943) Ice Growth model (left). In general, the model is able to predict the growth of sea ice, however, the model exhibits significant deviations from the observations during the fall freeze up and when the sea ice is insulated by a thick layer of snow.

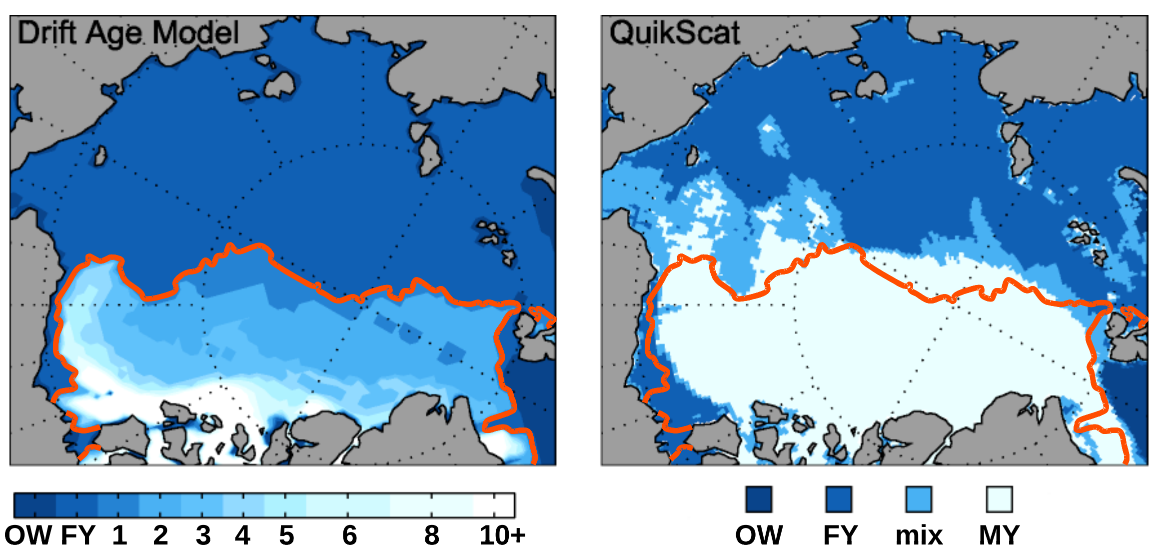

Figure 3: Comparison of sea ice distribution estimated using the drift-age model (March 2006, left panel) with QuikSCAT observations (21 March 2006, right panel). For ease of interpretation, the red line in both panels indicates ice age older than 1 year (i.e. perennial ice) as estimated by the drift age model.